Constraints on the origin of Manganese from the composition of the Sagittarius Dwarf Spheroidal Galaxy and the Galactic Bulge[1]

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ABSTRACT

The trend of [Mn/Fe] in the Galactic bulge follows the solar-neighborhood relation, but most stars in the Sagittarius dwarf spheroidal galaxy (Sgr dSph) show [Mn/Fe] deficient by ∼0.2 dex. This leads us to conclude that the Mn yields from both type Ia and type II SNe are metallicity-dependent. Our observations militate against the idea, suggested by Gratton, that Mn is over-produced by type Ia SNe, relative to type II SNe. We predict Mn/Fe ratios, lower than the solar neighborhood relation, for the younger populations of nearly all dwarf galaxies, and that Mn/Fe ratios may be useful for tracing the accretion of low-mass satellites into the Milky Way.

Subject headings: stars: abundances – nuclear reactions, nucleosynthesis, abundances– Galaxy: bulge – galaxies: dwarf – galaxies: individual (Saggitarius dwarf spheroidal)abundances, chemical evolution, bulge stars, galaxies: dwarf spheroidal

1. Introduction

In this Letter, we consider the abundance trend of Mn in three contrasting stellar populations: a sample of Galactic bulge K giants, giants from the Sgr dwarf spheroidal galaxy, and stars from the solar neighborhood.

The bulge population formed rapidly (Ortolani et al. 1995), on a timescale less than a few Gyr, as evident in the trends of alpha-element (e.g. O, Mg, Si, Ca, Ti) to iron ratios (McWilliam & Rich 1994; Rich & McWilliam 2000). Chemical evolution models of these abundance trends support an even more rapid enrichment timescale for the bulge, ≤ 1 Gyr (e.g. Matteucci et al. 1999).

Most dwarf spheroidal galaxies have extended star formation histories, lasting many Gyr (e.g. Mateo 1998, Grebel 2000), as reflected by their sub-solar trends of α/Fe and metallicity spread (Shetrone et al. 2001, Bonifacio et al. 2000 and Smecker-Hane & McWilliam 2003, hereafter SM03). The range of iron abundance for stars in the Sgr dSph exceeds a factor of ten, $-1.5 \leq$ [Fe/H] ≤ 0 dex (e.g. SM03). Thus, the Sgr dSph and Galactic bulge iron abundance ranges are nearly the same, which makes these systems ideal to compare and contrast.

Arnett(1971) predicted that Mn yields from type II SNe depend on the neutron excess, and so should be metallicity dependent. Woosley & Weaver (1995) computed yields for type II SNe, covering a range of masses and metallicity; their Mn/Fe yield ratios decreased by a factor of 3 from solar to one tenth solar metallicity, but below Z=$0.1Z_\odot$ the predicted yield ratio was constant.

Deficiencies of Mn, relative to Fe, in metal-poor stars were first noted by Wallerstein (1962), consistent with the odd-even effect for iron-peak elements suggested by Helfer et al (1959). G89 measured Mn in a sample of disk and halo stars, and found a roughly constant [Mn/Fe]≈-0.4 dex for [Fe/H]<-1, with the [Mn/Fe] ratio increasing linearly for [Fe/H]>-1, up to the solar [Mn/Fe] value.

Gratton noted that this behavior is opposite to the trend of alpha elements with [Fe/H].

In that case, the $[\alpha/\text{Fe}]$ ratio increases with decreasing $[\text{Fe/H}]$, and reaches a constant value of $[\alpha/\text{Fe}]\sim+0.4$ dex below $[\text{Fe/H}]=-1$. Tinsley (1979) explained this as due to the change in the ratio of type II to type Ia material, incorporated into stars at a given metallicity. Type II SNe arise from massive stars of initial mass $\text{M} \gtrsim 10\text{M}_\odot$, whose main-sequence lifetimes are a $\lesssim 10^8$ years. A type Ia SN arises in a binary system from mass transfer onto a white dwarf star (e.g. Iben & Tutukov 1987, Tornambè & Matteucci 1986), which explodes when the Chandrasekhar limit is exceeded; explosion times vary from $\sim 10^8$ yr to ≥ 10 Gyr after the stars were formed (e.g. Smecker-Hane & Wyse 1992).

In Tinsley's model, at low metallicity and early times stars were made from ejecta of type II SNe, rich in oxygen and other alpha elements. Type Ia SNe did not become significant sources of nucleosynthesis products until after ~ 1 Gyr when the metallicity had reached $[\text{Fe/H}]\sim-1$; at this point the low $[\alpha/\text{Fe}]$ ratios from type Ia SNe progressively reduced the ambient value until the solar composition was reached ≈ 4.5 Gyr ago.

G89 suggested that over-production of manganese in type Ia SNe could account for the observed $[\text{Mn/Fe}]$ trend using Tinsley's paradigm; indeed a bi-valued Mn/Fe yield ratio is perhaps the simplest assumption to make, based on the early observations.

Figure 1 summarizes the $[\text{Mn/Fe}]$ values from recent studies of Galactic stars for $[\text{Fe/H}] \gtrsim -2.5$; it shows a ~ 0.5 dex increase in $[\text{Mn/Fe}]$ from $[\text{Fe/H}]=-1.3$ to $+0.4$, roughly linear with metallicity. The Feltzing & Gustafsson (1998, hereafter FG98), Prochaska & McWilliam (2000, hereafter PM00[2]) and Reddy et al. (2003, hereafter R03) data have been put onto the same scale by applying corrections to ensure solar $[\text{Mn/Fe}]$ in the interval $-0.10\leq[\text{Fe/H}]\leq+0.10$. This normalization is not possible for the remaining studies shown in Figure 1; for those data we expect zero-point uncertainties near ~ 0.10 dex.

The FG98 results for metal-rich stars show $[\text{Mn/Fe}]$ increasing at higher $[\text{Fe/H}]$, whereas the $[\alpha/\text{Fe}]$ ratios remain constant; this suggests a metallicity-dependent yield for Mn produced by type Ia SNe, not Mn over-production by type Ia SNe.

Nissen & Schuster (1997) showed that thick disk stars possess α-element enhancements independent of $[\text{Fe/H}]$, yet the thick-disk stars in Figure 1 show a clear trend of increasing $[\text{Mn/Fe}]$ with $[\text{Fe/H}]$; this can be understood with a metallicity-dependent Mn yield from type II SNe.

The PM00/N00 data display a step in $[\text{Mn/Fe}]$, near $[\text{Fe/H}]=-0.7$, which may be associated with the transition from thin to thick disk populations, apparently confirmed by the slope of the R03 data. If real, the putative plateau might reasonably be explained by

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[2]The PM00 data are the Nissen et al. (2000) results with improved hfs corrections applied.

Mn over-production in type Ia SNe, or by a metallicity-dependent yield combined with the large metallicity dispersion in the Galactic disk age-metallicity relation. However, possible systematic errors that we suspected in PM00, and the lack of evidence for the step in the data of P00 and G89, cast doubt on the reality of this feature.

2.   Observations, Reductions and Analysis

High resolution (R=34,000–50,000) spectra of individual stars in both the Galactic bulge, through Baade's Window, and the Sgr dSph were obtained using the Keck I[3] telescope and echelle spectrograph (HIRES, Vogt et al. 1994); the typical S/N ratios were 50 per extracted pixel. Complete details of these two investigations can be found in SM03 and McWilliam & Rich (2003, in preparation). The Sgr dSph spectra were extracted using the IRAF suite of routines, whereas the bulge star spectra were extracted with MAKEE, written by T. Barlow. Line equivalent widths were measured using a semi-automated routine GETJOB (McWilliam et al 1995). From 1 to 4 Mn I lines were measured for each of the Galactic bulge giants, typically 3 lines. For the Sgr dSph from 4 to 10 Mn I lines were measured per star, most often 9 lines. Abundances were computed from the equivalent widths using the spectrum synthesis program MOOG (Sneden 1973) and the 64-layer Kurucz (1993) model atmospheres. The model atmosphere parameters were chosen, using photometric and spectroscopic methods, detailed in McWilliam & Rich (2003) and SM03. Since Mn I lines are strongly affected by hyperfine splitting, we employed line lists generated from published hfs constants or taken from Kurucz (1997) for the hyperfine components of each line, and then performed the appropriate synthesis to derive Mn abundances.

3.   Results and Discussion

3.1.   The Galactic Bulge

A plot of [Mn/Fe] versus [Fe/H] for the Galactic bulge stars is presented in Figure 2. The present data indicate that the bulge [Mn/Fe] trend is approximately the same as found fo solar neighborhood disk and halo stars, and even follows the local [Mn/Fe] trend for

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metal-rich stars.

We note that the bulge results are based on analysis of red giant stars, whereas the solar neighborhood points are almost exclusively from dwarf or turn-off stars; this may introduce zero-point abundance differences, expected to be less than 0.10 dex in [Mn/Fe]. To investigate zero-point abundance uncertainties for red giants we measured the [Mn/Fe] and [Fe/H] ratios for the thick-disk red giant Arcturus, using the Hinkle et al. (2000) spectrum. We found [Mn/Fe]=−0.23 and [Fe/H]=−0.56 for Arcturus, 0.075 dex below the mean [Mn/Fe] for the thick-disk dwarf stars of P00, in the range −0.63≤[Fe/H]≤−0.50. If the zero-point of the bulge [Mn/Fe] is increased by the 0.075 dex shift for Arcturus, agreement between bulge and solar neighborhood [Mn/Fe] is improved. We adopt the 0.075 dex zero-point shift as a measure of the systematic uncertainty of the red giant [Mn/Fe] abundance ratios in this letter; [Fe/H] for the red giants are accurate at the 0.10 dex level.

Figure 2 is inconsistent with the G89 scenario of Mn over-production by type Ia SNe. The high [α/Fe] and [Eu/Fe] ratios observed in bulge stars (McWilliam & Rich 1994, McWilliam & Rich 1999, Rich & McWilliam 2000) suggest nucleosynthesis in the bulge was dominated by type II SNe with a rapid formation time scale (e.g. Matteucci et al. 1999), with element ratios similar to the halo but at higher overall metallicity. Thus, if type Ia SNe over-produced Mn then bulge stars would show a deficiency in [Mn/Fe] ratios; but such a deficiency is not observed. The [Mn/Fe] trend seen in Figure 2 is entirely consistent with a metallicity-dependent yield for Mn in type II SNe.

If type II SNe produce a metallicity-dependent Mn yield above [Fe/H]=−1, then the linear trend of [Mn/Fe] with [Fe/H] for the Galactic bulge stars in Figure 2 is consistent with evolution characterized by rapid recycling of the gas, as in the Simple Model (Searle & Sargent 1972), which assumed a closed box and instantaneous chemical recycling. Rich (1990) first showed that the bulge iron abundance distribution can be fit by the Simple Model, and this is confirmed by Zoccali et al. (2003) using iron abundances inferred from $V - K$ photometry. Thus, the bulge [Mn/Fe] trend with [Fe/H] supports the metallicity-dependent Mn yield for type II SNe (above [Fe/H]=−1), suggested by Arnett (1971) and Woosley & Weaver (1995). More data would be helpful for confirming these conclusions; in this regard it would be useful to measure the [Mn/Fe] trend in bulge stars well below [Fe/H]∼−1.

3.2. The Sagittarius Dwarf Spheroidal Galaxy

In Figure 3, we present the results for [Mn/Fe] in the Sgr dSph. The most obvious feature is that the metal-rich Sgr dSphs stars with [Fe/H] $\gtrsim -0.6$ have [Mn/Fe] values that lie well below, by 0.2 dex, those of solar neighborhood stars.

The Sgr dSph and Galactic bulge abundances were computed with spectra of similar quality, with the same atomic parameters, model atmosphere grid, and temperature scale. Systematic zero-point differences and random errors are unable to explain the difference between our Sgr and bulge [Mn/Fe] ratios.

The unusually low [Mn/Fe] ratios in Sgr dSph are inconsistent with Mn over-production in type Ia SNe, suggested by G89. The low [α/Fe] ratios (see SM03) strongly suggest that type Ia SNe dominated the nucleosynthesis of iron-peak elements in this galaxy for [Fe/H] $\gtrsim -0.6$ dex. Given an increased nucleosynthetic contribution from type Ia SNe in the Sgr dSph, [Mn/Fe] ratios enhanced over the solar neighborhood ratios are expected if Gratton's hypothesis is correct. Our observations of *deficient* [Mn/Fe] ratios in Sgr dSph stars are opposite of this expectation.

Observations of s-process neutron capture elements in the Sgr dSph show that ejecta from the old, metal-poor, AGB population dominated the chemical enrichment of the neutron-capture elements, in the epoch probed by stars with [Fe/H] $\gtrsim -0.6$ (SM03). In this paradigm for the Sgr dSph the old, metal-poor, AGB stars must have been accompanied by low-metallicity type Ia SNe, which we assume dominated iron production prior to the formation of the [Fe/H]≥-0.6 population. This picture of the chemical evolution of the Sgr dSph provides a natural explanation for the observed low [Mn/Fe] values, if the Mn/Fe yield ratio increases with metallicity in type Ia SNe: the low [Mn/Fe] ratios reflect the fact that iron-peak nucleosynthesis was dominated by the metal-poor type Ia SNe population.

If all Sgr dSph stars with [Fe/H]≥-0.6 possess the same [Mn/Fe] ratio, then it must be that element yields from low-metallicity SNe ([Fe/H]≤-1) completely overwhelmed products from more metal-rich stars. On the other hand, an upward slope of [Mn/Fe] with [Fe/H] would indicate a detectable contribution from metal-rich type Ia and type II SNe, albeit dwarfed by the metal-poor type Ia component. More data is required to distinguish between these two possibilities. In either situation the current data argue that the old, metal-poor, population produced much more iron-peak enrichment through type Ia SNe than the younger, metal-rich, populations produced via type Ia and type II SNe.

Since the Mn/Fe ratios in Sgr are the consequence of slow star formation and significant mass loss, other dwarf spheroidal systems with extended star formation histories should exhibit similar abundance trends. In this regard it would be very useful to study the trend

of [Mn/Fe] in the Magellanic Clouds and Local group dSph systems, such as the Fornax dSph. We note that sub-populations in the bright Galactic globular cluster ω Cen possess some chemical similarities to the Sgr dSph. Deficient [Cu/Fe] ratios in ω Cen (Cunha et al. 2002) may indicate a chemical enrichment history similar to Sgr dSph, but at lower overall [Fe/H]. We predict that the most metal-rich stars in ω Cen will show deficient [Mn/Fe] ratios, and stars in Sgr dSph possess low [Cu/Fe] ratios.

The chemical enrichment model proposed by SM03 for Sgr dSph involves delayed injection of nucleosynthesis products from an old, metal-poor, population and suggests a relatively high ratio of metal-poor to metal-rich stars. This condition is expected of galaxies which lose a significant fraction of gas over long timescales and galaxies which accrete pristine material sufficient to maintain a large metal-poor fraction. The model qualitatively explains the unusual chemical composition of the Sgr dSph stars, but no quantitative modeling has been undertaken; thus we cannot yet say what fraction of old, metal-poor, stars is required to produce the observed abundance ratios. To quantitatively constrain the models we must first obtain unbiased age and [Fe/H] distributions for Sgr dSph stars.

Even near solar metallicity stars in the Sgr dwarf have [Mn/Fe] significantly lower (by $\sim$0.2 dex) than stars in the disk/bulge. Thus, if Sgr-like systems fell into the bulge and were so thoroughly mixed that no trace of their distinct kinematics remained, it would still be possible to infer their presence through the depressed [Mn/Fe] and [α/Fe] ratios, and enhanced s-process abundances.

4. Summary

We report on the abundance trends of manganese in the Galactic bulge and the Sagittarius dwarf spheroidal galaxy. Both stellar populations show a general trend of [Mn/Fe] increasing with higher [Fe/H]; but while the bulge follows roughly the solar neighborhood [Mn/Fe] trend, the trend in Sgr is lower by $\sim$0.2 dex. We believe that this offset reflects the less rapid chemical evolution of the Sgr dwarf compared to the Galactic bulge and solar neighborhood. Similar trends should be present in all dwarf galaxies, where chemical enrichment over long time scales reached metallicities greater than [Fe/H]=-1. The low Mn abundance at a given [Fe/H] could be used to identify stars from accreted dwarf galaxies in large-scale surveys of the disk and bulge.

The [Mn/Fe] trend in the Galactic bulge suggests a metallicity-dependent yield of Mn in type II SNe, qualitatively consistent with the predictions of Arnett (1971) and Woosley & Weaver (1995). A metallicity-dependent Mn yield from type II SN is supported by the trend

of [Mn/Fe] in local thick disk stars which are known to have constant, enhanced [α/Fe]. Given the rapid bulge formation timescale (Matteucci et al. 1999), the metallicity dependence of the Mn/Fe yield ratio is likely very similar to the observed trend; in this regard it will be interesting to measure [Mn/Fe] in metal-poor Galactic bulge stars.

The deficient [Mn/Fe] ratios in the Sagittarius dwarf spheroidal galaxy implies a metallicity-dependent Mn yield for type Ia SNe; this is supported by the observations of FG98, which show increasing [Mn/Fe] in metal-rich disk stars, at constant [α/Fe]. The idea that Mn is over-produced by type Ia SNe, as suggested by G89, is ruled-out by these observations.

One complication in our interpretation is the apparent offset in [Mn/Fe] between thin and thick disk stars, which appears consistent with Mn overproduction in type Ia SNe, but contrary to the [Mn/Fe] trend in the metal-rich disk stars of FG98 and the Sgr dSph. If this offset is real it might be understood as the consequence of a metallicity-dependent yield combined with a large metallicity-dispersion in the thin-disk age-metallicity relation.

We have insufficient information to state the form of the metallicity-dependent yield for type Ia SNe, other than it is lower at low [Fe/H]. Further understanding of Mn/Fe yields will be made with detailed chemical evolution models for Sgr dSph, but this will require measurement of the detailed age and [Fe/H] distribution functions for this galaxy.

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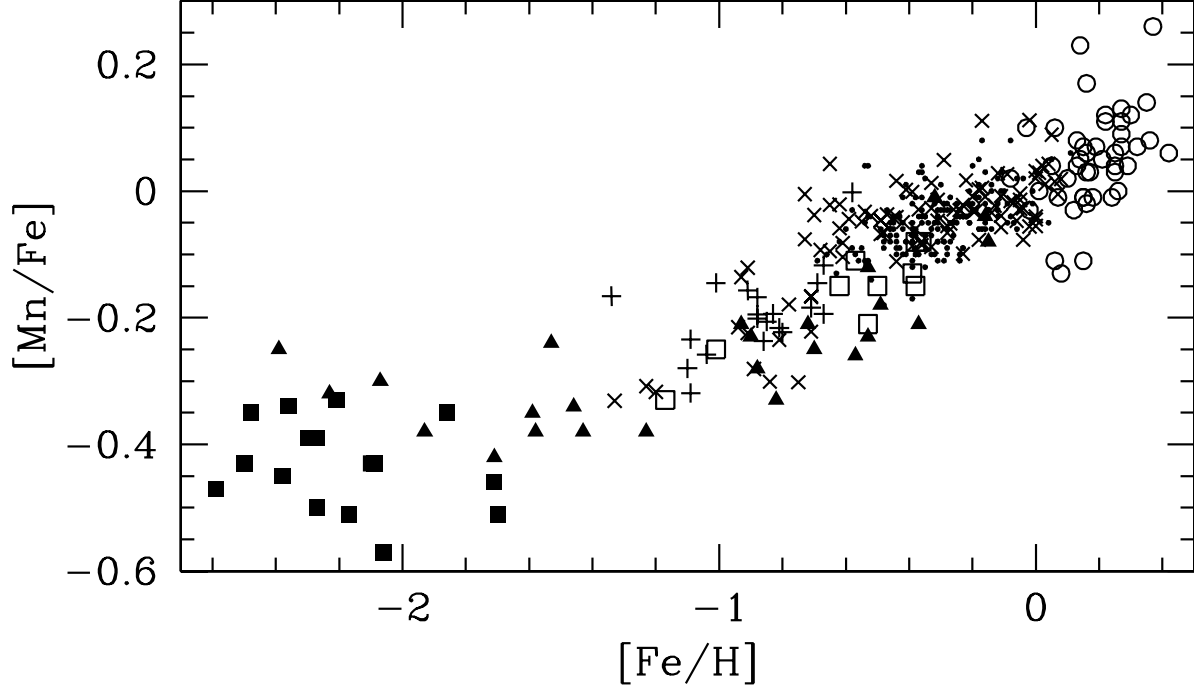Zoccali, M., Renzini, A., Ortolani, S., Greggio, L., Saviane, I., Cassisi, S. et al. 2003, A&A, 399, 931

Fig. 1.— [Mn/Fe] from numerous studies. Dots from R03, crosses: PM00/N00, pluses: thick disk stars from PM00/N00, open circles: FG98, triangles: G89, open squares: P00, and filled squares: Johnson (2002). Johnson (2002) analyzed red giants, G89 studied a mix of dwarfs and giants; all others employed dwarf or turnoff stars. Zero-point corrections have been applied to the PM00/N00, R03 and FG98 data: $+0.02$, $+0.10$, and -0.06 dex respectively. General systematic errors in [Mn/Fe] are likely less than 0.10 dex, and random uncertainty of individual points typically 0.06 dex; the [Fe/H] uncertainty is $\lesssim 0.10$ dex. Johnson (2002) stars and G89 having stars [Fe/H] $\lesssim -1.2$ are likely halo objects. G89 stars having $-1 \leq$ [Fe/H] $\lesssim -0.5$ are likely thick disk members.

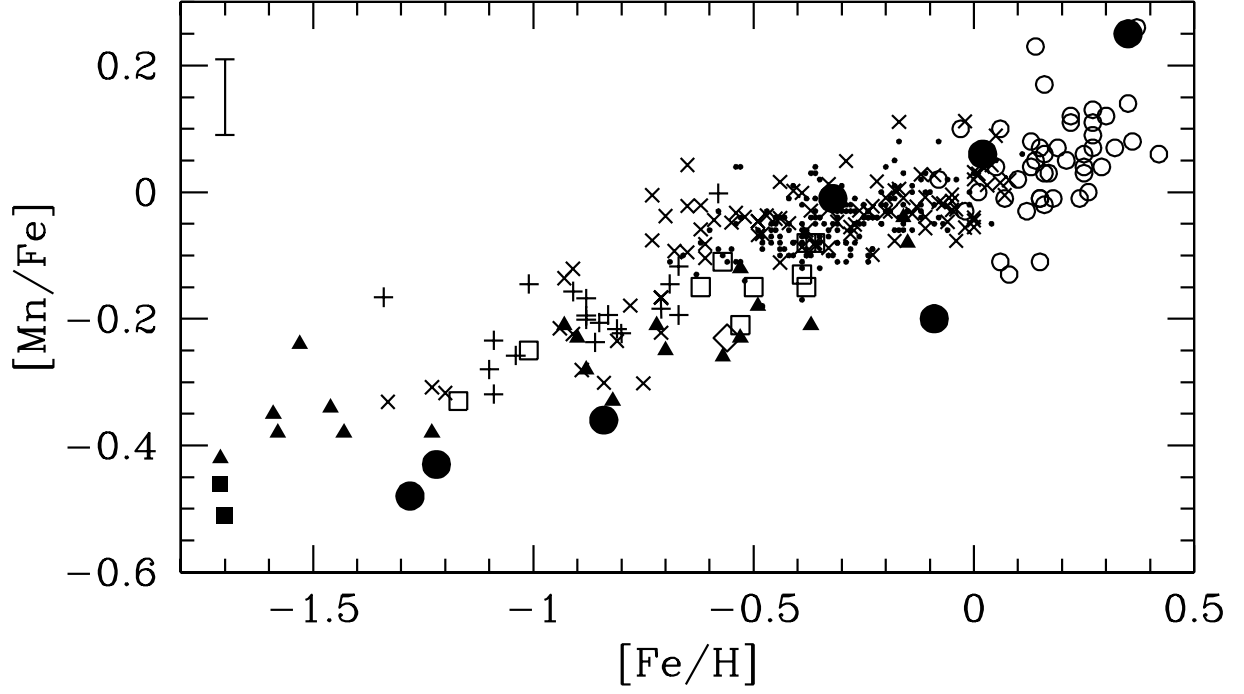Fig. 2.— Same as Fig. 1, but with bulge stars (filled circles) and Arcturus (open diamond) added. The error bar indicates 1σ scatter of [Mn/Fe] from Mn lines, not the error on the mean [Mn/Fe] value. Although α-elements and Eu are enhanced in bulge giants, Mn follows the Galactic disk relation. This would not be the case if Mn were over-produced in type Ia SNe.
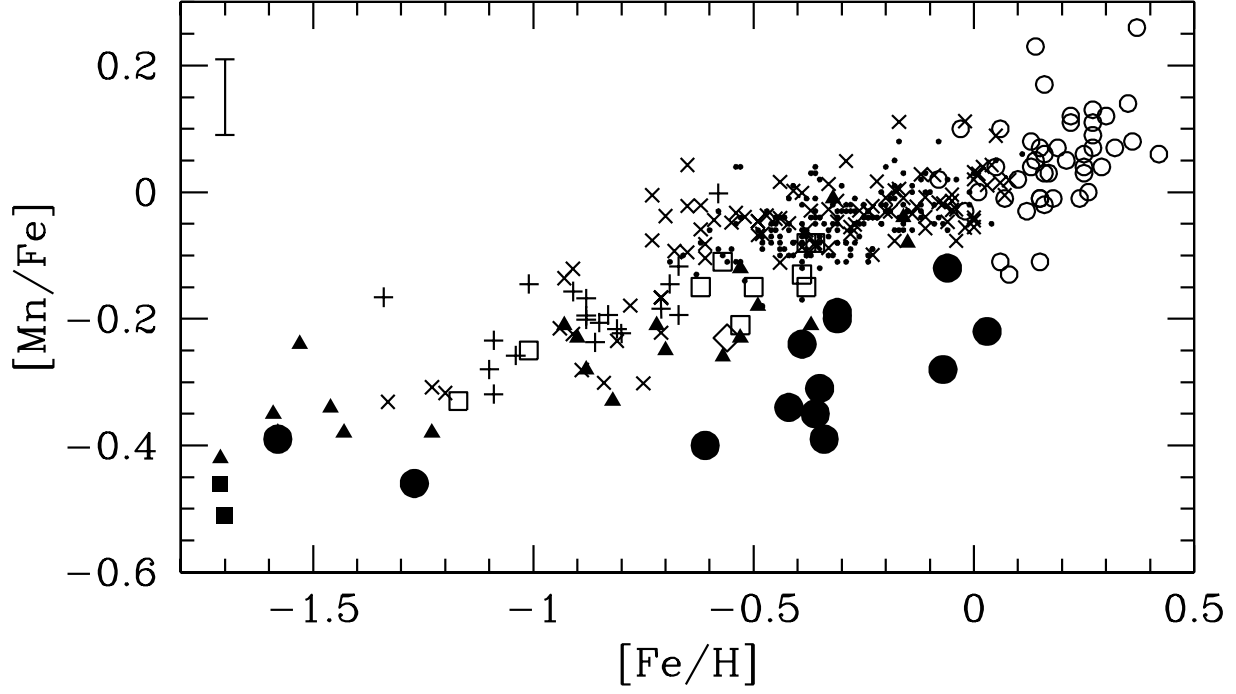
Fig. 3.— Same as Fig. 1, but with Sgr dSph stars (filled circles) and Arcturus (open diamond) added. The error bar indicates 1σ scatter of [Mn/Fe] from Mn lines, not the error on the mean [Mn/Fe] value. We propose that the low [Mn/Fe] ratios in Sgr dSph is a consequence of enrichment of the interstellar medium by metal-poor type Ia SNe.